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AGROECOLOGICAL ASPECTS OF EVALUATING AGRICULTURAL R&D

Stanley Wood and Philip G. Pardey

Environment and Production Technology Division

International Food Policy Research Institute
1200 Seventeenth Street, N.W.
Washington, D.C. 20036-3006 U.S.A.

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ABSTRACT

In this paper we describe how biophysical data can be used, in conjunction with agroecological concepts and multimarket economic models, to systematically evaluate the effects of agricultural R&D in ways that inform research priority setting and resource allocation decisions. Agroecological zones can be devised to help estimate the varying, site-specific responses to new agricultural technologies and to evaluate the potential for research to spill over from one agroecological zone to another. The application of agroecological zonation procedures in an international agricultural research context is given special attention.

Keywords: biophysical, economic evaluation, international R&D, research priorities.

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by Stanley Wood and Philip G. Pardey[*]

1. INTRODUCTION

Environmental considerations have always played a part in agricultural technology design, development, adoption, and performance. This is clearly so for research related to the soil, water, and biological inputs in agriculture; the so-called natural resource focus of agricultural R&D. But agroecological factors are equally important when analyzing agricultural R&D performance from a commodity perspective. Moreover, while conserving natural resources for their own sake may have some social value, it is the efficiency with which they are used as inputs into agricultural production systems that is properly the primary point of departure for much agricultural R&D.

In this paper we describe how agroecology is useful in evaluating agricultural R&D and allocating research resources.[1] Specifically we review the principal means by which agroecological factors are currently taken into account in research evaluation and discuss the

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[*] Senior scientist and research fellow respectively in the Environment and Production Technology Division of the International Food Policy Research Institute, Washington, D.C. The authors are grateful for the discussions they have had on this topic with Don Winkelmann, Peter Jones, and John Corbett but naturally absolve them of any responsibility for the contents of this paper. Revised version of a paper prepared for the IFPRI Ecoregional/2020 Vision Workshop, 7-9 November 1994, Airlie House Conference Centre, Virginia, USA

[1] Although we also recognize that the policy environment within which technology choice and use decisions are made has direct and significant implications on the size and, particularly, the distribution of research benefits.

prospects for progress in both the conceptual framework and the operational tools of agroecological analysis in this context.

While many of the issues are of general relevance we highlight some agroecological issues that are of special significance for the international agricultural research centers (known as the Consultative Group on International Agricultural Research, CGIAR, or CG for short). The CG involves 16 research centers with various commodity, regional, and scientific mandates operating on a global scale. These centers ostensibly undertake research with broad applicability but in reality face tradeoffs in targeting low versus high potential areas, in pursuing growth or income distribution objectives, and in giving greater emphasis to the environmental consequences of agricultural R&D. Declining support for international research has sharpened the need to economize and heightened the need to systematically evaluate the impacts of past research and the prospects for current and proposed work.

While there is a widely-held view that more explicit recognition of environmental aspects is essential for improving the conduct and evaluation of agricultural R&D, there remain persistent conceptual and methodological problems in extending the existing framework to accommodate them. But real progress has been made and more progress is possible. We argue that a fruitful way forward is to better articulate the appropriate scope, scale, and aggregation relationships between R&D and agroecology. Precisely how best to do this is not fully resolved but we present some approaches that are being tried and provide some critical evaluation of them.

2. BIOPHYSICAL SPACE FROM AN R&D PERSPECTIVE

For R&D evaluation purposes an agroecological zone can be viewed as a geographical area exhibiting sufficiently homogeneous ranges of key biophysical variables as to make it useful in the stratification and evaluation of R&D targeted to specific objectives. This notion of an agroecological zone has a number of features that complicate its implementation in practice. These include:

- Determining for which R&D objectives and activities agroecological factors are relevant
- Determining the key variables that might be appropriate and under what circumstances
- Determining “sufficiency" of homogeneity
- Characterising and physically locating the relevant boundaries of agroecological domains

There is a long and rich history of representing geographical space in ways that are biophysically consistent. The most frequently encountered and simple to construct representations are based on the spatial interpolation of point climate data or derived climate variables such as evapotranspiration and length of growing period. Examples include the climate classification systems of Köppen (1923), Papadakis (1966), Holdridge (1967), and FAO (1978). These schema were developed for continental and regional scale characterisation of relatively homogeneous climate zones within which major natural ecosystems and agricultural systems would likely occur. The most recent of these are the ecoregions developed by the technical advisory committee, TAC, of the CGIAR. These ecoregions, based on groupings of FAO-defined agroclimatic zones with some arbitrary adjustments to better coincide with national boundaries, are discussed in the subsequent section.

At a similarly broad level of definition are the major ecosystems of the world such as tropical rainforests, savannas, prairies, and deserts. These are often typified by the dominant natural vegetation but have evolved through the dynamic interaction of climate and land. They have the distinct advantage of being observable (at least in a natural state) and, thus, of being more unambiguously delimited than agroclimatic zones. Although highly aggregated they have provided a clear spatial focus to several international agricultural R&D initiatives -- particularly those investigating the mitigation of human-induced changes such as deforestation and desertification. There are also, for example, international R&D efforts to ameliorate the inherently poor soil fertility of tropical savannas in an attempt to unlock the food production potential of these major tracts of land in South America and Africa.

Watersheds and landscape units are increasingly perceived as logical spatial units of analysis as agricultural R&D pays more attention to the natural resource consequences of policy and technological change. A major attraction of watersheds and landscape units such as hillsides, valley bottoms, hillcrests, and deltas is their suitability for monitoring both on-site and many off-site effects of agriculture and agricultural R&D. These physiographically delimited units have strong spatial relationships to the flux of natural resources, principally water and soil but also, often by consequence, natural vegetation. Although physiographic units are observable and thus amenable to delimitation, this process requires more detailed data, usually at scales of less than 1:250,000. The current major R&D effort on the hillsides of Central America being undertaken by three CG centers CIAT, CIMMYT, and IFPRI, among others, and the Inland Valley Agroecosystems work of IITA (Thenkabali and Nolter

1995) are examples of this type of spatial focus. It has been proposed that this focus will be fostered to a greater extent in the CG (TAC/CGIAR 1996).

At more detailed scales the spatial variability of soils becomes a dominant biophysical factor. This was recognised in FAO's definition of agroecological zones or AEZs (FAO 1978) as representing unique combinations of agroclimatic zones and soil units that would likely be homogeneous with regard to their capacity to support (rainfed) production of a wide range of food and cash crops. FAO's implementation of the concept of AEZs does not include any physiographic dimension, other than is implicit in the correspondence between physiography and soil units; for example, the occurrence of fluvisols in river valleys.

The fundamental challenge discussed in this paper is how to define spatial biophysical units that best help in anticipating the likely productivity and natural resource consequences of agricultural R&D. Since we are mostly concerned with ex ante impact assessment the challenge has several components. They are to delimit spatial domains where new technologies are likely to have impacts, to distinguish areas within those domains where impacts will be significantly different, and to do all this as expeditiously and cheaply as possible. This latter constraint implies the need to use readily available and often quite aggregate thematic biophysical data. Given this perspective we focus on ways of defining agroecological zones and, similarly, agroclimatic and agroecoregions that improve our ability to evaluate agricultural R&D.

CGIAR/TAC ECOREGIONS

The nine ecoregions proposed by TAC are aggregations of the agroclimatic zones delineated by FAO using two derived climate variables, one based on temperature regime (resulting in 14 *major climates*) and the other on moisture availability (generating 20 *length of growing periods*).[2] To simplify the correlation of country boundaries with ecoregions, geographically limited occurrences of agroclimatic zones in any country were discounted (Kassam 1991). In this schema, 39 countries (57% of the sample) were classified as having a single agroclimatic zone and 14 countries (21%) were assigned only two zones. TAC has broadly described ecoregions as "agroecological zones regionally defined" (Gryseels and Kassam 1994, p.3); despite the fact they are based on agroclimatic and not agroecological zones. More recently, while retaining the concept of ecoregions as an overarching priority setting and resource allocation device at the CG level, TAC has suggested that to be adopting an ecoregional approach R&D must "address landscape units in the agroecosystem of a priority agroecoregional zone (TAC 1996, p.69)." The underlying message appears to be that even though the defined ecoregions are highly aggregated, actual R&D needs to be much more sharply focused. While we subscribe to that point of view, we argue that to serve any useful purpose for R&D evaluation, even aggregated agroecological units must be more spatially consistent with the expected impacts of the agricultural R&D agenda.

It has been argued elsewhere that the ecoregions used by TAC fail to provide a satisfactory framework for relating either agricultural R&D or productivity growth to agroecological domains even at global or regional levels (Wood and Pardey 1993, Craig, Pardey and Roseboom 1994). However, the TAC ecoregion experience, and in some respects that of CIMMYT and its megaenvironments, is valuable in pointing to the difficulties faced

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[2] Not all of the 280 possible combinations occur, and some only occur in single continents or sub-continents.

in adopting a top-down approach to the definition of ecoregions.[3] Clearly these were exploratory institutional responses to the gathering impetus for including *explicit* agroecological perspectives in the management and conduct of research. However, ecoregions are based on levels of aggregation of ecological space that are difficult to reconcile with research activities, even at the major programmatic level. The boundaries of the fixed, extensive areas they represent are unlikely to correspond to the specific agroecological criteria most relevant to any current or planned research portfolio.[4]

This potential mismatch represents more than a scientific problem. In pursuit of greater transparency, objectivity and, ultimately, research performance, TAC is committed to placing greater reliance on formal priority setting procedures; procedures that currently embody their problematic ecoregions. And these procedures in turn inform resource allocation decision making at the highest level (Gryseels et al. 1992). Because of their importance in the allocation process, TAC's ecoregions may serve to divert rather than to focus research resources and priority setting deliberations. The very existence of an overarching classification, regardless of its scientific merit, results in resources being spent on developing methods for re-casting classifications found useful at the operational level to match the classification adopted at the institutional apex for research planning, funding, monitoring, and evaluation (e.g., Hunt’s (1993) proposed method of linking "IRRI AEZs" to TAC's ecoregions). Furthermore, there may be spurious signals of the relevance of the current ecoregions as they increasingly feature in project proposals. It will be difficult to

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[3] For a more complete description of CIMMYT's megaenvironments see CIMMYT (undated).

[4] CIMMYT's megaenvironments, while highly aggregated, are at least commodity specific, i.e., there are separate maize and wheat megaenvironments.

determine which proposals genuinely view ecoregions as a conceptually sound basis for research, and which simply view ecoregions as a means of accessing funds earmarked on an ecoregional basis (Alston and Pardey 1996).

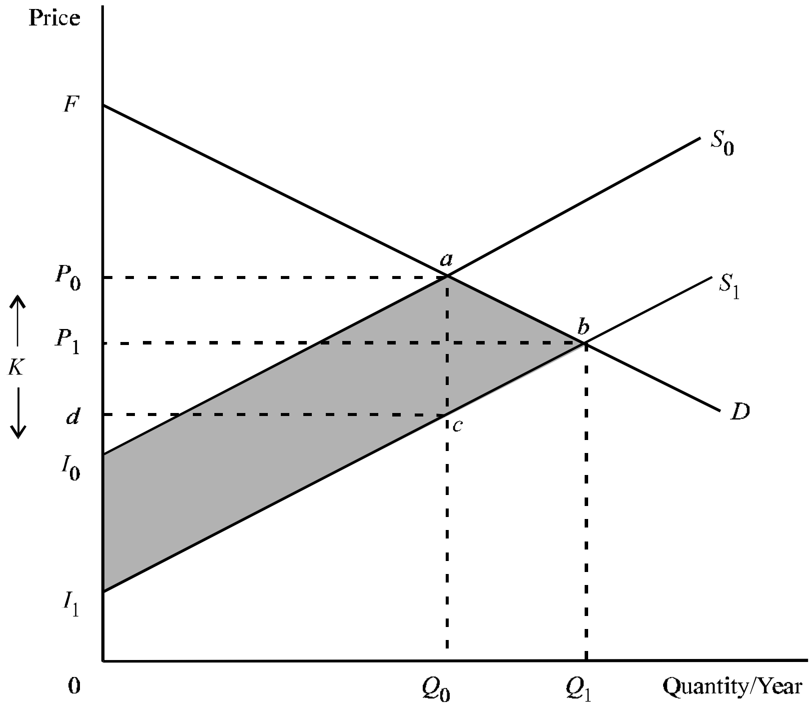
As already noted, the operational response of most CG centers to demands for a more explicit natural resource orientation in research has been to develop ecosystem- and landscape-oriented programs based on hillsides, savannahs, forest margins, natural forests, highlands, tropical coral reefs, and so on. This approach signals the stronger and more tangible correspondence between research problems and ecosystems than between research problems and ecoregions. TAC's deliberations on allocating CG resources would seem better served by drawing on the agroecologies actually used by individual centres or particular research programs within and across centres.

3. AGROECOLOGIES AND ECONOMICS

An economic approach to evaluating R&D begins with the basic, commodity market model of research benefits depicted in figure 1: S_0 represents the supply function before a research-induced technical change, and D_0 represents the demand function. The initial price and quantity are P_0 and Q_0. Suppose research generates yield increasing or input saving technologies. These effects can be expressed as a per unit reduction in production costs, K, that are modeled as a parallel shift down in the supply function to S_1. This research-induced supply shift leads to an increase in production and consumption to Q_1 ($\Delta Q = Q_1 - Q_0$), and the market price falls to P_1 (by $\Delta P = P_0 - P_1$).

Consumers are better off because R&D enables them to consume more of the commodity at a lower price.

Figure 1: *The Basic Supply-and-Demand Model of Research Benefits*



Although they receive a lower price per unit, producers who adopt the new technology are better off, too, because their unit costs have fallen by an amount, *K* per unit, that is more than the fall in price. Total benefits are obtained as the sum of producer and consumer benefits.[5] As an approximation, the cost-saving per unit multiplied by the initial

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[5] The consumer surplus measure of the consumer benefit is equal to area P_0abP_1, i.e., rectangle P_0aeP_1 (= $Q_0 \times \Delta P$) plus triangle *abe*. The producer surplus measure of the producer gain is equal to area P_1bcd in figure 1, i.e., rectangle P_1ecd (= $Q_0 \times [R - \Delta P]$) plus triangle *bce*. Note rectangle $P_0acd = K \times Q_0$ is often a close approximation of total benefits because triangle *abc* is relatively small.

quantity, $K \times Q_0$, is often used. Thus the size of the market, as indexed by the initial quantity Q_0, as well as the size of the research-induced savings in the per unit cost of production, K, are critical factors in estimating the economic benefits from R&D. Better estimates of K mean better estimates of the benefits from research, and a better basis on which to allocate scarce research resources.

Given the site-specific nature of much agricultural R&D, knowledge of the agroecological factors that shape the various biophysical responses to a new technology -- be it a new seed variety or a new crop management practice -- can substantially improve the estimate of K used to calculate the benefits from research. Our approach is to identify biophysical boundaries or agroecological zones that delineate areas thought likely to have fairly uniform responses to R&D. We then seek information about the expected research effects (the K's) in each zone. A weighted sum across the zonal K's, using, say, market shares as weights in the aggregation, is likely to yield a more informative and accurate estimate of the overall K compared with an approach that leaves this aggregation process implicit or undefined.[6]

Identifying "homogeneous" agroecologies also helps in modeling and measuring the potential spillover effects of agricultural R&D. If K_1 is the unit-cost reduction realized from research done in zone 1, then an understanding of the characteristics of the zones and technologies enables the estimation of the *relative* unit cost changes, θ_{12}, if the zone 1 technologies were to be applied in zone 2 (i.e., $K_2 = \theta_{12} K_1$). The potential spillover effects arising from technology transfer can then be established. Using biophysical information this

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[6] Wohlgenant (1996) develops in some detail the analytics of aggregating across different groups of producers, with different cost structures, facing different R&D effects.

way provides insights into the economic tradeoffs involved in targeting technologies to a particular agroecology (i.e., maximizing K_1 relative to K_2, with, perhaps, a correspondingly low θ_{12}) versus developing technologies that have a high spillover potential (i.e., maximizing θ_{12}).

While the creative use of agroecological and biophysical data is particularly useful for assessing the *potential* productivity and natural resource degradation consequences of R&D, the *realised* consequences are influenced by a host of other factors. These factors include investment in infrastructure that provide transportation, communication, education, and health services, as well as market factors such as the economic structure of the agricultural sector and the distorting policies of government.

A significant effort has gone into developing agroecological approaches to assessing the local and spillover potential of agricultural R&D. These approaches have in turn been incorporated into multimarket trade models that make it possible to place an economic value on the consequences of R&D (Alston, Norton, and Pardey 1995). Used in this way, multimarket models have the capacity to capture both spatial variation in the effects of R&D that primarily have an agroecological dependence and the spatial variation in market factors that span agroecological domains.

Such models can also incorporate exogenous (i.e., non-research induced) and spatially variable shifts in supply and demand. This makes it possible to directly model the interactions between government policies, R&D, and the size and distribution of the social benefits from research. Work is also underway to extend these models to assess the potential natural resource consequences and other externality effects of R&D (Alston, Anderson, and Pardey 1995).

4. AGROECOLOGICAL ANALYSIS AND RESEARCH GOALS

Wood and Pardey (1993) examined the relationship between agroecology and the research goals of growth and equity, as well as natural resource degradation concerns, and identified various roles for agroecological analysis in addressing these issues. While many of the links between the spatial focus and the economic consequences of research are known to be important, they are not always well understood. The presumption that there are worthwhile gains to be had from improving our understanding of these linkages is attracting the increasing interest of researchers and research policymakers alike.

The growth cum productivity consequences of new agricultural technologies are clearly linked to the ecological adaptability ranges of commodity species and sub-species as well as those of their pests and diseases. Thus, the traditional strategies for improving land productivity -- intensification and rehabilitation -- have important ecological dependencies. But it is not just in identifying opportunities for, or constraints to, improved *land* productivity that ecological analysis can assist in analysing research options. A significant number of the technologies for improving the productivity of labor and other agricultural inputs are also conditioned by ecological circumstances. For example, the areas suitable for tractor use are limited by slope considerations, among other things, while manual cultivation technologies are generally ineffective in areas of vertic soils.

In many circumstances the distribution of income and the impact of research on that distribution also have agroecological dimensions. Marginal, inaccessible, and otherwise environmentally fragile lands are often the areas left to be farmed by poorer farmers who (together with the urban poor) are the most usual target groups for equity oriented research.

Thus, while the set of conditions that can engender and sustain poverty is very broad, there are clearly circumstances in which both the spatial and temporal patterns of agroecological phenomena play an important role.

Natural resource degradation issues are also inexorably linked to agroecological domains. Whether concerns relate to the on-site or externality consequences of production, such as soil erosion and water pollution, or to longer term intergenerational issues of access to natural resources (e.g., productive soil stocks or conservation areas that preserve biodiversity), many of the causal and controlling factors involved have an agroecological dimension.

While agroecology is clearly relevant for the growth, income distribution, and natural resource degradation consequences of research, it is equally clear that the set of agroecological domains relevant to each may be quite different. Thus, domains appropriate for the optimum yield performance of specific germplasm may not be those that characterise the epidemiology of pests that could ultimately limit yields. Furthermore, neither of these domains may coincide with those that best represent the land degradation hazards of nutrient leaching or soil erosion.

This brings us to the question of scope. Only by first determining the appropriate scope of research objectives and the concomitant research portfolio is it possible to meaningfully define the scope of the ecological domains that need to be characterised. The primary purpose in developing the FAO agroclimatic zones that constitute the biophysical aspect of the CG's ecoregions was to assess the production potential of rainfed *crops*. This gives the CG ecoregions an implicit crop science emphasis leaving the effects of other technologies to be somehow "accommodated" in that same framework. Does such an approach adequately represent the business of the CG system across all its research goals and programs? If not, how can the scope be manageably broadened while simultaneously making agroecological groupings that have some practical value, albeit at a highly aggregated level?

Within any given scope of analysis there also remains the question of tailoring the ecoregional characterisation to the specific research issue at hand. Table 1 sets out research management issues at various institutional "scales" and for each of those issue cum scale combinations identifies what role agroecological analysis may play. It shows that agroecological analysis of some kind is appropriate for strategic concerns at the regional and national levels down to the site-specific, operational level. These ideas are analogous to the notions of multi-scale characterization described by Andriesse et al. (1994).

Two general areas of application for agroecological analysis clearly emerge from the table:

- Using agroecological zones as a means of stratifying relatively homogeneous research *problem* domains
- Using agroecological zones as a means of stratifying relatively homogeneous research *impact* domains

This is a subtle but important distinction since within any problem domain it is likely that research- based technology solutions will have varying spatial consequences. Experience has shown that scientists commonly think in terms of the first set of domains in planning their research, while economists think of the latter in assessing potential research benefits.

Table 1 Research evaluation and agroecological analysis

	Potential Contribution of Agroecological Analysis	Remarks
Research evaluation and priority setting issues		
Identify economies of scope and cale Where would (and would not) collaborative or complementary research initiatives be advantageous?	Identify areas having either similar or, in some important way, dissimilar ecological characteristics that may improve the efficiency of research, e.g., shuttle breeding, multi-location trials.	The national and institutional incentives to participate in such joint initiatives will be largely determined by the perceived distribution of potential research benefits, e.g., intellectual property rights, trade effects.
Technology targeting Where will what technologies be most appropriate, and for whom?	Identifygeographical areas -- AEZs -- expected to exhibit relatively homogeneous physical response to the application of new technologies. Zones can be delineated that address either the production or natural resource consequences of R&D. In many places there is also a relationship between fragile lands and disadvantaged social groups.	(a) Some zoning methods are summarised in figure 1. GIS techniques are rapidly expanding options. (b) Importance of adopting compatible levels of aggregation and classification for environment, production systems, and research descriptors.
Quantifying research effects What is the likely level of economic effect (cost reduction, benefit) of new technologies on the targeted groups?	(a) Zones can provide a means of stratifying the research effort, e.g., a basis for eliciting the expected effects of research from scientists. (b) By using crop performance and simulation models quantitative assessments may be made of research effects on potential production and natural resource degradation in each AEZ.	(a) Account should be taken of changes in environmental adaptability that new technologies may be designed to achieve. (b) Even the "physical" assessments of likely effects make important socioeconomic assumptions.
Spillover potential To what extent may technologies developed in or for one area be usable in, or adaptable for, other areas?	Identify potential technology spillovers by analysing spatial patterns of productivity and the (physical) production constraints which may help account for those patterns.	Same as "Quantifying Research Effects" section.
Operational research management issues		
Research problem selection What research problem and technology mix?	Analyse targeted and spillover effects at disaggregated commodity, environment, and technology or discipline level. Estimate likely effects of research that seeks to alter agroecological responses.	Need for broad-based crop and livestock models - encompassing both productivity and environmental factors.
Tradeoff of research effects How best to tradeoff expected effect against R&D lag times and expectations of research success.	All of these research determinants have some dependency on the agroecological domain in which research is conducted	These relationships are explored in some ex-ante research evaluation methods, (Davis, Oram and Ryan 1987, Pardey and Wood 1994).
Experiment design What experiments and experimental designs?	Facilitates the choice of an appropriate mix of AEZs. Defining the spatial extent and severity of physical constraint or degradation areas.	Need for statistical verification of appropriate AEZ framework.
Site selection Which experimental sites?	Facilitates choice of sites that are representative of AEZ target zones.	Identify sites with no or few constraints or sites having specific abiotic, biotic, or degradation characteristics of relevance to the experiment.

Source: Wood (1994).

5. CHARACTERISING AGROECOLOGICAL ZONES

Choosing the most appropriate variables to characterize agroecological domains may seem a relatively trivial task, but in practice is one that often calls for many significant tradeoffs and one that generates its own set of analytical problems.[7] Perhaps the most fundamental constraint in the selection process is the current state of scientific knowledge. We can only characterise research problem or impact domains in terms of agroecological variables that we know, or are presumed, to have significant influence. However, as discussed earlier, there are still many phenomena such as the incidence of plant and animal pests and diseases or the incidence of natural resource degradation where the role of ecological processes, although known to be important, is poorly understood.

Characterising agroecological space depends largely on the geographical scale and the scale of the research management problem, as depicted in table 1. In practical terms this involves jointly dealing with:

- interactions between the analytical framework and data availability and management
- homogeneity and aggregation issues
- criteria for establishing agroecological boundaries

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[7] Such as the overspecification of criteria. For example some of CIMMYT's megaenvironments are classified by both temperature and elevation, the latter being a temperature proxy in tropical areas. This inevitably produces classification anomalies in practice (Corbett 1991).

ANALYTICAL FRAMEWORK - DATA INTERACTIONS

The selection of variables used to characterize agroecological zones should not be a haphazard process but should be based on some conceptual model of the role of ecology appropriate to the geographical scale and the set of research management and evaluation issues at hand. Thus, our understanding of plant growth processes may suggest the use of a minimum set of variables that capture the influences of radiation, water availability, and soil nutrient status, whereas knowledge of land degradation processes may suggest the need for terrain, soil erodibility, rain energy, and land use or land cover variables. The specific conceptual model most appropriate and the level of aggregation implicit in the parameters of that model are simultaneously conditioned by data availability and data management constraints.

Data Availability

As geographical areas increase so do the difficulties of obtaining a consistent set of agroecological data such as climate, physiography, soils, and land use of sufficient resolution to reflect spatial variation that may be significant from a research perspective. The scarcity of such data has been a significant binding constraint to advances in agroecological analysis. However, for regional and global applications, this situation is changing quite rapidly as spatially referenced datasets become increasingly available.

To date, agroecological analysis in the CG has been largely synonymous with *agroclimatic* analysis because of issues of data availability and also because of the greater relative importance of climatic characterisation variables at the regional scale.[8] Climate data are, in general, readily available and their use is either direct (for instance, maximum temperature may be both the observed variable and the parameter used to define an agroecological boundary) or is embedded in some internationally recognised derivative such as Penman potential evapotranspiration estimates. While other variables such as land use or cover and soil type are also important, both limited availability and availability in disparate classification systems have been major obstacles to their use.[9]

Information Management

Managing large, complex, and frequently revised biophysical datasets is a rapidly diminishing problem but one that influenced many earlier approaches to agroecological characterisation. The simple way to handle this problem has been to impose limits on the geographical scale and on the number of variables used to classify agroecological domains. Notably, these shortcut or approximation approaches have rarely been subject to any type of sensitivity analysis to ensure that the most important parameters are the ones used for characterisation.

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[8] The influence of geographical scale on variable selection is described by Gillison and Brewer (1985): "At global and continental levels ... climate appears to be the prime determinant for the living resource. With increasingly finer scale, climate becomes less important and terrain and edaphic factors become better predictors of living resource patterns. The problem of establishing an objective way of matching environment attributes with scale will be a function of the scale and the purpose of the resource survey under consideration."

[9] Their relative scarcity is determined both by the greater (and frequently discontinuous) variation in space and because of the complexity of characterisation of soils, vegetation, land use, and so on. Consequently it is more expensive to gather this type of information.

Another common strategy is iterative aggregation to derive composite indices from a range of ecological and other variables. For example in the FAO agroecological zones studies that underlie the CG ecoregions, five climate parameters are used to estimate Penman potential evapotranspiration,[10] and then rainfall, potential evapotranspiration, and an assumed soil moisture holding capacity are used to derive a length of growing period variable (FAO 1978-81). It is the length of growing period variable that is subsequently used to delineate the water availability boundary of AEZs in the FAO schema.

However, there are other factors that mean information management remains an important consideration. One is the approach advocated in this paper of using the power and flexibility of information technology to maintain basic data in unclassified formats, interpreting and classifying it only as appropriate to specific purposes. Another factor is the increasing availability and higher resolution of satellite imagery. Both of these place growing demands on computer storage and processing capacity that are likely to at least keep pace with parallel advances in computer technology.

HOMOGENEITY AND AGGREGATION

We have argued for procedures that can generate problem-specific agroecological domains. These domains must be as broad as possible to minimise the number of domains to be dealt with, but as narrow as necessary to adequately define the spatial context of important research problems or research effects. Within such domains we would like the set of research problems or technology effects to be somehow similar, or at least not significantly dissimilar.

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[10] The five parameters are maximum temperature, minimum temperature, relative humidity, wind speed and incoming radiation, all measured on a monthly basis.

This is one of the issues embodied in our notion of an agroecological zone: how to determine the similarity or homogeneity of a zone as viewed from an agricultural R&D perspective?

In any situation the appropriate number and complexity of agroecological domains will be influenced by the scale of the research management issues being addressed and the extent to which we are willing or able to define the likely set of research problems or the likely set of technology effects that the associated research portfolio may encompass. In this context, defining agroecological zones at the CG-wide level when research can range across forestry, crops, and livestock clearly presents a formidable challenge. The challenge suggests in concept, what appears true in practice, that the broader the scope of an agroecological domain the less is its practical value in evaluating any meaningful grouping of research endeavours, even at high levels of aggregation.

However our ability to adequately describe research is only one part of the problem. Agroecological homogeneity can only be judged by the interaction of research and the environment and so must also relate to the intrinsic complexity of the agroecological factors involved. Clearly agroecological variables that change rapidly in space or time are more difficult to characterise in homogeneous groups. With very complex phenomena, such as soils, shorthand ways of expressing variation have been developed. For instance there are methods of soil classification that can reduce a plethora of detailed site, horizon, physical, chemical, and mineralogical information into a summary set of standardised taxonomic descriptors, such as USDA's soil taxonomy scheme (Soil Survey Staff 1994). While such classification is inevitably associated with loss of data precision in some variables, this may be more than compensated by the linkages it provides to generic information about each soil class. The approach can also provide economies in resource surveys by focusing data collection effort on the key variables that delineate classes. However, the diagnostic criteria of an established classification system may well be based on ecological variables or ranges of those variables that do not coincide with those required for specific agricultural research purposes. For this reason, among others, research continues on new ways to represent the spatial variation of individual soil attributes (Bouma 1989, Webster and Oliver 1989a and 1989b).

While, say, soil taxonomy is a useful means of condensing many variables recorded in one location into a simple descriptor (e.g., soil type) it only partially solves the issue of handling variability. At practically all other scales than the individual site we are also confounded by spatial variation of soil and terrain properties that, unlike climate parameters, are still difficult to interpolate by automated means.[11] This is generally handled by recognising spatial *patterns* of variation and describing domains in terms of those patterns. The domains or mapping units represented on soil, vegetation, and land-use maps that are digitised for incorporation into most GIS databases are already in this aggregated format. Although by linking to the tables that define the composition of patterns (e.g., a map legend) we can make analyses that preserve the recorded heterogeneity, it requires expert guidance or a set of expert rules to attempt to spatially locate those analytical elements within the mapping units. There are additional analytical challenges if the analysis must be based upon the overlay of two or more such preaggregated maps.

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[11] The automated interpolation of most climate parameters at a regional scale is much more reliable because their variation is better correlated to location, i.e., latitute, longitude, and elevation.

One approach to minimising this problem would be to always use the most detailed resource information, no matter what level of research management analysis is being performed. But there are practical limitations imposed by the techniques of spatial data analysis and presentation. For printed map formats that constitute the current source of most GIS data, general cartographic standards dictate that, regardless of the scale, individually drawn map elements (polygons) should not be smaller than around 0.25 to 0.40cm.[12] The practical implication is that as maps change scale, say, as we zoom-out to smaller scales, there is a need to simplify map contents by smoothing boundaries and even eliminating smaller polygons.

Even in computer-based GIS analysis of spatial data there still remain some significant constraints. In vector-based GIS programs such as ARC/INFO there are physical limits attached to the number and complexity of mapping units in a single map (or coverage) but even before those limits are reached the time and computer resources required for map management and analysis can become excessive. In a raster-based system such as IDRISI the limitation is the number of image cells (pixels) and the complexity of the information held for each pixel. However, there are two significant advantages of the raster domain. First, pixels can be so small relative to the whole image that a quasi-continuous (agroecological) surface can be represented.[13] Second, since each pixel can be separately classified, the representation of spatial variability can be much more realistic with adjacent pixels being assigned to totally

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[12] This represents 62,500-100,000ha on a 1:5,000,000 map of the type used in FAO's global study for mapping AEZ's, or 2,500-10,000ha on the 1:500,000 or 1:1,000,000 scales commonly used in national analyses.

[13] On a regional scale, e.g., Africa or Latin America, a raster image usually has a resolution of 5-10 are minutes. Thus an individual pixel represents 6,000-23,000 ha.

different agroecological zones if they meet the relevant classification criteria. Thus, much more underlying spatial heterogeneity can be preserved than in equivalently scaled maps or vector-based GIS applications.

ESTABLISHING BOUNDARY CRITERIA

Following a review of agroecological characterisation practices in Latin America and the Caribbean (Wood and Pardey 1993), a general classification has been made of the main methods of characterising agroecological space, including those of the international agricultural research centres located in the region (Wood 1994). There are three basic approaches:

- *Deductive methods.* A priori, expert-based specification of agroecological boundary criteria considered appropriate to the research portfolio or to specific research programs. The criteria are then applied to a spatial database of agroecological variables resulting in the delineation of ecological domains (zones). Two approaches are common, namely the definition of *generic* zones and the definition of *R&D-specific* zones.
- *Cluster analysis.* Statistical grouping of similar agroecological conditions using cluster analysis followed by an expert based assignment of clusters into classes appropriate to research.
- *Production geography (inductive method).* Ecological characterisation of specific geographical areas having known research problems or expected to display similar

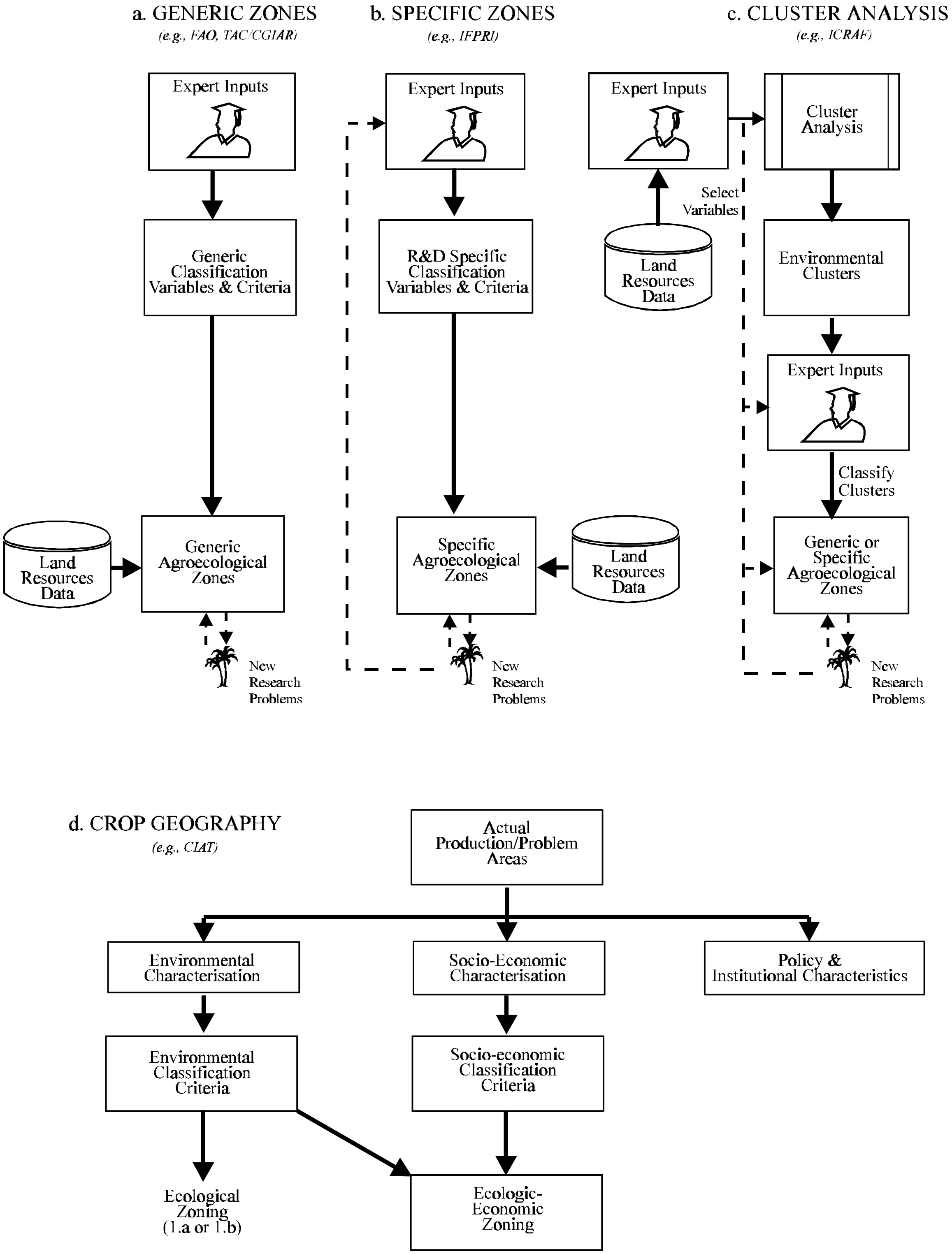
responses to new technologies. The derived characterisation is then used to identify similar ecological zones in other geographical areas

All methods have the same first steps, namely determining the scope and scale of the research management issues involved. This could involve the experimental design of a research project focusing on root crop blight, planning a livestock sector program, or making decisions on resource allocation at the national level across the entire research portfolio. This should determine the geographical extent and geographical scale of representation as well as the most appropriate ecological variables. The approaches then proceed along different routes as summarised in figure 2.

Generic Zones

On the basis of the overall range of potentially researchable issues associated with production systems and natural resource degradation hazards, a general set of ecological variables and classification or boundary criteria is defined (figure 2a). When applied to the resource database of a given geographic area, those criteria translate into spatial boundaries that delineate generic zones. Various FAO studies, including the global AEZ project, adopted this approach (FAO 1978-81). Because the TAC/CGIAR research priority setting methodology described by Gryseels et al. (1992) utilises FAO's AEZs (at a more aggregated, continental scale -- the CAEZ), generic zoning is inherent in the TAC/CGIAR ecoregions.

Figure 2: *Some approaches to agroecological zoning in the CGIAR system*



a. GENERIC ZONES
(e.g., FAO, TAC/CGIAR)

b. SPECIFIC ZONES
(e.g., IFPRI)

c. CLUSTER ANALYSIS
(e.g., ICRAF)

d. CROP GEOGRAPHY
(e.g., CIAT)

R&D Specific Zones[14]

In this approach a new set of ecological criteria (both variables and boundary values) can be defined to suit the specific ecological context of research targeted to different production systems or resource management problems (figure 2b). Thus scope- and scale-specific zones can be delineated that represent the current "best-fit" ecological divisions of space for research evaluation purposes. This is the approach that the International Service for National Agricultural Research (ISNAR) adopted in several of its collaborative country-level research evaluation and priority setting studies (Pardey and Wood 1994) and undergoing continued refinement by staff of the International Food Policy Research Institute (IFPRI).

Cluster Analysis

Here the starting point is not the specification of research-related boundary criteria, but analysis of natural resource data (figure 2c). Although conditioned by the prior specification of characterisation variables and statistical control parameters, an otherwise unhindered grouping of statistically similar agroecological clusters is obtained. Once defined these clusters can be interpreted and classified by scientists to assess their relevance to specific research issues.

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[14] In the reference quoted (Wood and Pardey, 1993) these were originally termed dynamic zones. This terminology has been changed (a) because of the possible interpretation that the method shifts the zone boundaries over time, and (b) to avoid confusion with the term "dynamic crop environment classification" used by Corbett (1993) to describe a combination of spatial interpolation and cluster analysis, where the greater part of the dynamics is associated with the capability to re-estimate climate surfaces.

Production Geography

In this approach the starting point is the actual geographical location of production (figure 2d). This distribution can be characterised from a number of perspectives including agroecology, socio-economics, and the institutional and policy environment. The characteristics so identified can then be used to delineate potentially similar zones in other geographic areas. This approach is also valid when thinking about natural resource conditions, for example for characterising the conditions under which land degradation takes place.

All of these methods have their strengths and weaknesses. From one perspective the generic and specific zone methods are similar. An extremely disaggregated set of generic zones -- i.e., many classification criteria and, hence, zone boundaries -- could conceivably be aggregated into different sets of (specific) zones for each new research management issue. In practice, however, classification boundaries for generic zone systems tend to be oriented to general cartographic needs and seldom coincide with the requirements of any specific set of research issues. By contrast, the criteria used in specific zoning can be selected to be the most appropriate for the on-going or planned research.

Before the advent of computer-based GIS, zones were delineated manually in map format. Generic zones then had the distinct advantage that zoning was performed only once, regardless of the number and type of production systems being studied. The significant disadvantage, however, is that the zones so delineated often have considerable spatial mismatch with the agroecological adaptability of specific production systems or with the occurrence of resource degradation. The specific zones approach overcomes this problem since it redefines zones to match the precise requirements of the research issues addressed.[15] By virtue of tailoring the classification criteria to the task at hand, these specific zones should not only result in better boundary location, but should also display greater homogeneity within those boundaries. The approach has the overhead of requiring zones to be updated as new production systems or natural resource issues are analysed, and updating often involves the addition of new variables and new delimiting criteria by digitising or spatial interpolation. Thus, the approach is only practical with ready access to GIS capabilities.

Cluster analysis takes a fundamentally different approach by not predefining classification boundary values, but by selecting only the set of ecoregional characterisation *variables* from which statistically significant environmental cluster boundaries (characterisation criteria) are deduced. Expert judgement is then used to match these statistically determined clusters with, say, areas of germplasm adaptability or natural resource management problems. This is not always easy. Experts must make judgements in a multi-variable context (compared with generic and specific zones where variables are generally treated independently)[16] and there is not necessarily a correspondence between the statistically determined cluster boundaries and the spatial performance potential or degradation hazard of individual production systems. There are also important analytical choices to be made on the most appropriate ecological distance algorithm and on the "target" number of clusters, both of which affect the clustering results. Cluster analysis is similar to the generic zones

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[15] The limits of precision are defined by (a) the extent to which the production and natural resource system requirements or tolerances are known and (b) the level of aggregation inherent in the underlying environmental data.

[16] This is not to say that the independence (or, more specifically, ceteris paribus) assumption is more scientifically defensible; rather that it has proved a more practical way of eliciting expert opinion on crop requirements and tolerances.

approach if analysis for new research issues is made by a reinterpretation of existing cluster groupings. More specific zoning can be achieved either by regrouping clusters into new classes or by redefining the set of ecological variables and repeating the entire cluster analysis. Clustering provides a systematic and reasonably reproducible means of aggregating ecological space.

The production geography approach is manpower intensive but does allow for the most specific characterisation of production environments. In this sense it comes closest to the ideal of enabling the identification of homogeneous ecological areas with respect to research problem identification. However, the approach is by definition limited to current practices, practices that do not necessarily provide reliable indicators of the likely effect of new technologies. For example, research may seek to significantly shift the environmental adaptability range of a crop or to improve its tolerance to geographically specific pests and diseases. In this case the new technology may have the potential to define a different production geography. Overall, the crop geography approach may be seen as a scientific approach to simultaneously determining productivity, adoption, and resource degradation criteria that could be used in any of the ways described above to help delineate zones beyond the current areas of production.

Figure 3 highlights some additional classification issues -- a fundamental one being that *all* approaches rely upon expert scientific judgement. Since not all ecological characteristics are yet amenable to computer-based spatial interpolation,[17] the manually-interpolate-then-digitize approach is widely practised. It is also clear that the vector-based

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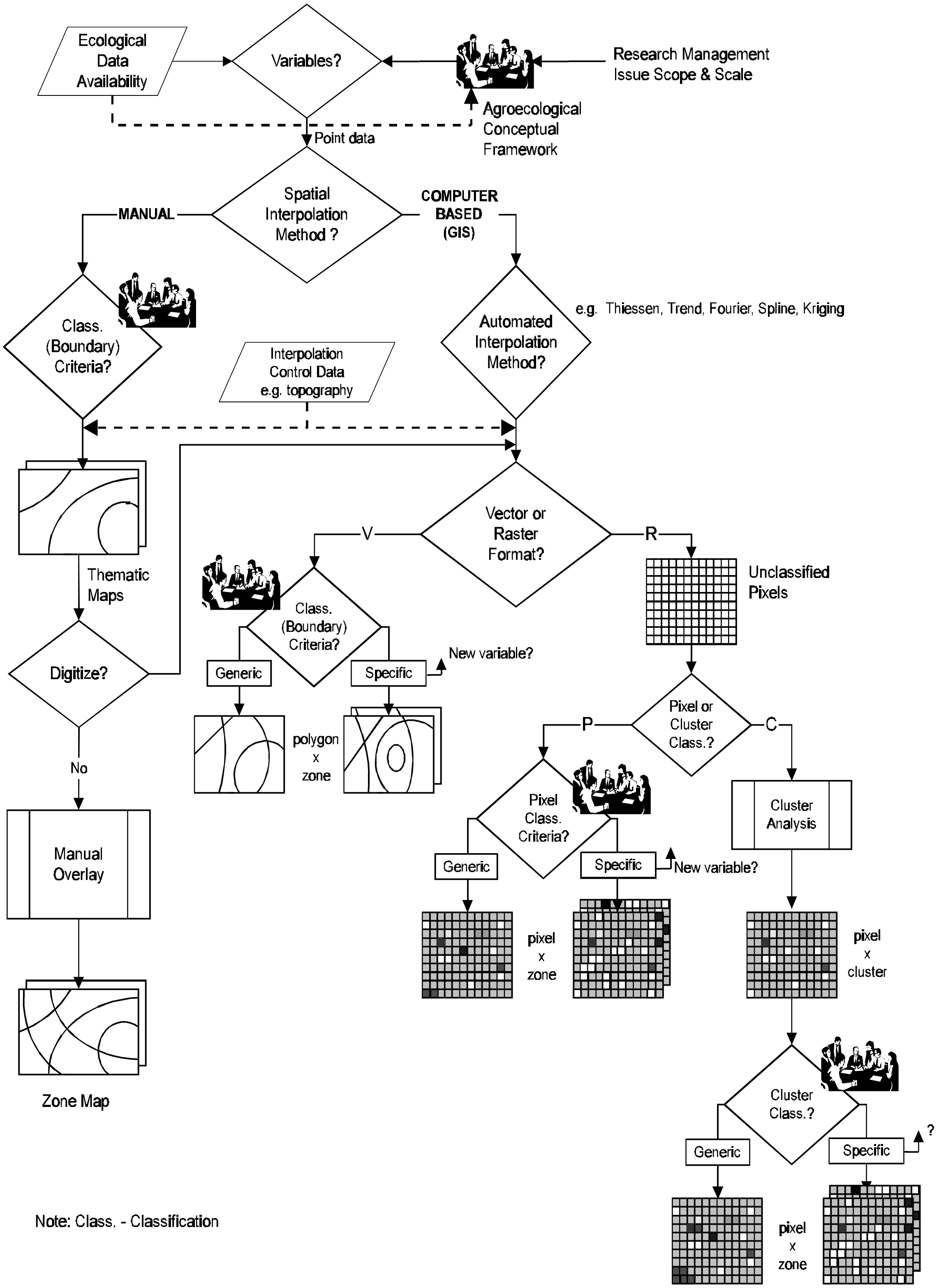
[17] And there may be good technical reasons why manual interpolation is more reliable even in cases when computer based interpolation is a feasible option.

Figure 3: *Some GIS related options involved in agroecological characterisation*



Note: Class. - Classification

GIS approaches tend to force a higher degree of classification than raster systems since there are practical, operational limits on the maximum number and minimum size of polygons for analysis, plotting, and labelling purposes. For ecological analysis the raster domain is more flexible, and pixel data can be stored in an unclassified form with little or no loss of information. Furthermore, for display and plotting purposes there is no minimum contiguous area requirement; in the limit an agroecological zone could be represented by a single pixel.

Figure 3 shows how, in the raster domain, a choice must be made either to directly classify pixels according to expert elicited criteria or to first perform a cluster analysis and then allow experts to classify clusters. This choice may be conditioned by the bounds of knowledge on the ecological tolerances and requirements of a relevant species or sub-species. For most food and cash crops it is most likely that adaptability limits and tolerances are fairly well known, in which case we prefer to directly classify pixels by expert elicitation. If, on the other hand, relatively little is known apart from existing geographic distribution, as appears to be the case with many tree and shrub species, then clustering can be a useful means of deducing important boundary criteria and identifying ecologically homologous areas.

6. FLEXIBILITY IN AGROECOLOGICAL CHARACTERIZATION AND MAPPING

Agroecological zone boundaries cannot be considered as fixed. They are best treated as variable, not only because of global and local changes in the environment but also, and often more significantly, because of the means we have at our disposal to estimate and represent them. Specifically, agroecological boundaries can change for at least three reasons:

MORE AND BETTER DATA

As more information becomes available on topography, climate, soils, vegetation, and land use both from conventional surveys and remote sensing, our underlying ecological databases are enriched and we obtain increasingly better definition of agroecological variables in time and space. Thus, even if our classification criteria remain unchanged, the physical boundaries of agroecological domains may be revised as a consequence of improved data.

As a specific example we consider two rasterized elevation datasets for South America. The first is based on a 10 arc minute grid (NOAA 1988), representing approximately an 18 km by 18 km grid at the equator, and the second is based on a 5 arc minute grid (NOAA undated). The same simple elevation classification schema was applied to both datasets and the resulting areas allocated to each elevation class are summarized in table 2. There are significant differences in the areas assigned to several classes important from an agricultural perspective, for example 32.3 million hectares difference (8.55%) in the below 100 meter class, and 19.4 million hectares difference (-12.5%) in the 500 to 750 meter range. Clearly if such orders of discrepancy are encountered in even a few agroecological characterization variables the consequent spatial delineation of zones could vary markedly.

Furthermore, given the interest in environmental change and the formulation of change scenarios, the availability of data on the likely spatial patterns of temporal change could add another dimension to agroecological characterisation, particularly in the context of research into the long-run aspects of natural resource degradation.

Table 2 Effect of different data sources on estimating the distribution of biophysical variables

Elevation Range	Area in South America		Difference in Area	
	10 minute grid	5 minute grid		
	(hectare)	*(hectare)*	*(hectare)*	*(%)*
< 100	344,432,119	376,745,484	32,313,365	8.58
100 - 250	488,575,049	486,303,911	-2,271,138	-0.47
250 - 500	422,833,930	407,522,087	-15,311,842	-3.76
500 - 750	174,941,577	155,510,271	-19,431,306	-12.50
750 - 1000	110,537,550	114,736,527	4,198,976	3.66
1000 - 1500	67,714,788	67,059,805	-654,983	-0.98
1500 - 2000	33,697,144	37,671,808	3,974,664	10.55
2000 - 2500	22,903,904	23,537,639	633,735	2.69
2500 - 3000	20,941,254	17,701,454	-3,239,799	-18.30
3000 - 3500	17,373,245	16,791,202	-582,043	-3.47
3500 - 4000	35,330,087	38,894,839	3,564,752	9.17
> 4000	42,589,354	39,394,973	-3,194,380	-8.11
Total	1,781,870,000	1,781,870,000		

Source: Calculated by the authors from digital images generated by the National Oceanic and Atmosphere Administration (NOAA 1985 and undated)

IMPROVED DATA INTERPOLATION AND INTERPRETATION ALGORITHMS

Even if both the underlying databases and the classification criteria remain unchanged, agroecological boundaries will shift because of improved means of converting the primary, observed data into the derived values often used for classification. For example, Hutchinson's generalised cross validation (GCV) spline fitting algorithm has rapidly become an accepted means of improved spatial interpolation of climate data (Hutchinson 1991). Another example is the on-going work on "pedo-transfer" functions to deal with the spatial interpolation of soil attributes (Bouma 1989, Webster and Oliver 1989 a and b).

Advances are not limited to spatial interpolation but also to the estimation of derived parameters. Examples are the improvements in the estimation of potential evapotranspiration

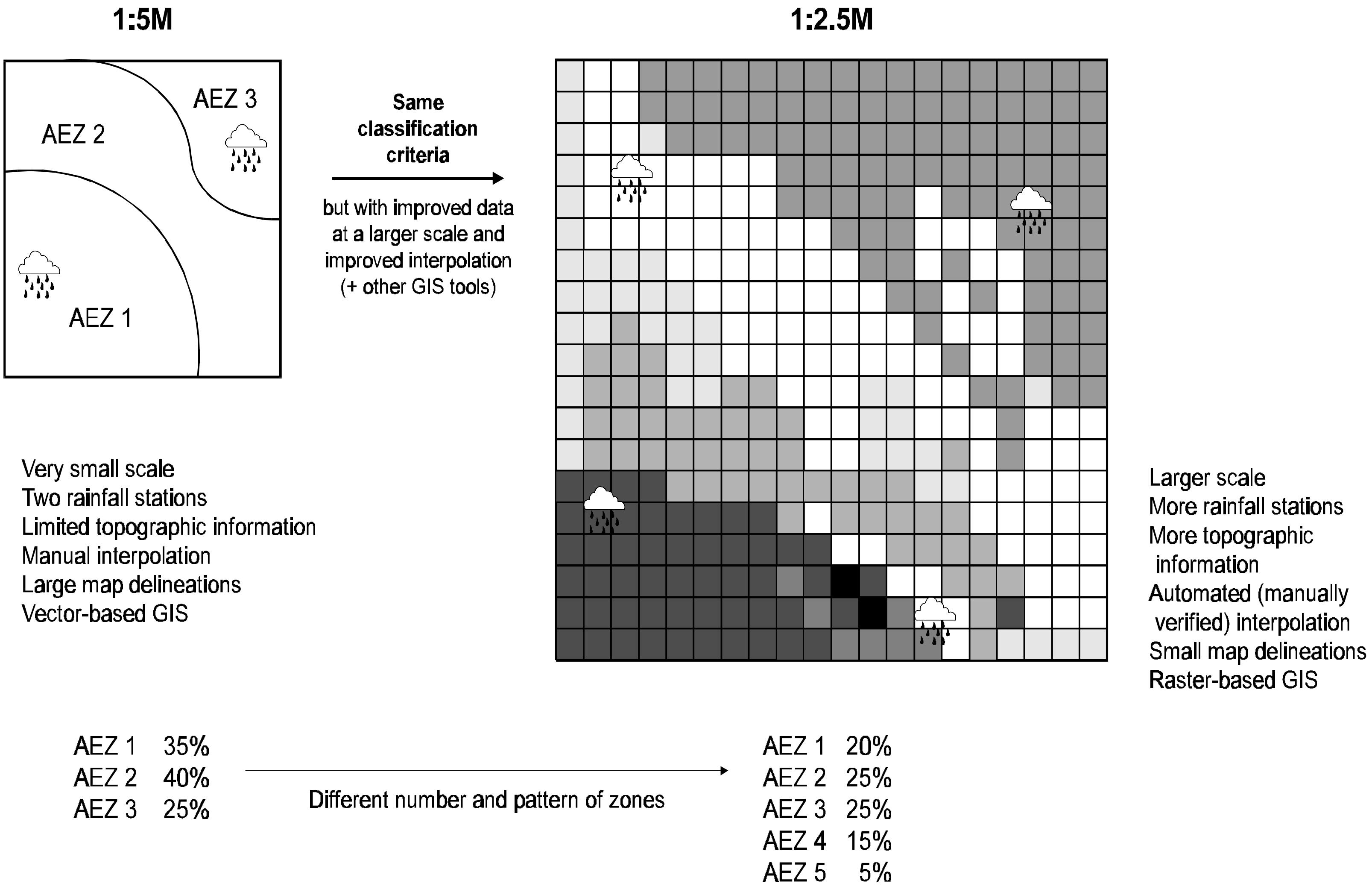
(FAO 1990), and improvements in FAO's algorithm for estimating the length-of-growing period (Fischer et al. 1995). The sophistication of derived parameters is increasing in other ways, primarily through the use of process models that integrate the effects of variables otherwise treated independently in the standard "overlay" approach to zoning. Thus, crop simulation models can be used to integrate climate, soil, and plant characteristics to derive measures of yield that could be taken as agroecological characterisation variables (both in space and time).

SCALE AND AGGREGATION

We have already seen that as scales become smaller we are forced to reassess the complexity of spatial information. This may include both simplifying boundaries and eliminating map elements (while, hopefully, preserving the physical if not spatial characteristics of those elements in associated tabular formats). Thus, both the boundaries and the composition of agroecological domains are likely to change as we change scales. The need for such aggregations as we move to smaller scales is greater for manually drawn maps than for vector-based GIS, which in turn is greater than for raster-based GIS.

Thus the meaningful development of agroecological concepts cannot be built around a concept of fixity -- in terms of variables, boundary values of those variables, nor the physical location of agroecological boundaries. Figure 4 illustrates this last point by showing how the factors just described can alter both the spatial and non-spatial characterisation of agroecologies even if characterisation variables and boundary values remain fixed. At the mapping scale and with the data resolution shown in the left hand rectangle the geographical

Figure 4: *The impacts of scale, data availability and spatial interpolation methods*



area is deemed to contain three agroecological zones; AEZ1 is 35% of the total area, AEZ2 is 40% and AEZ3 is 25%. If we could now zoom-in on that area with a different data resolution and perhaps with additional information, such as the additional rainfall stations shown, the result could be the rectangle shown on the right. Applying identical classification criteria to this could produce a significantly different number and spatial pattern of zones. Clearly if any research activities or institutional mandates were tied to a specific agroecological zone there would be an on-going need to review their geographical purview as scales changed and datasets improved.

7. CONCLUSION

Agroecology has a real role to play in designing and evaluating agricultural research and development strategies. In recognition of that potential, the CG system is also moving to the use of agroecological criteria as explicit factors in its institutional structure and in the strategic deployment of its research resources. However we question whether the implementation of the ecoregional concept as described by Gryseels et al. (1992) provides any meaningful correspondence with the spatial domains targeted by the international agricultural research centers. For the reasons outlined in this paper, TAC could gain much by adopting a more flexible approach to dealing with the agroecological aspects of agricultural R&D. The same would be so for other agencies operating at regional, national, or local scales of inquiry.

For most research evaluation purposes there are persuasive reasons why flexible rather than fixed notions of agroecological space are preferred. Indeed there appears little justification for preaggregating space into fixed agroecologies given the current opportunities afforded by our agroecological knowledge base, information technology, and greater accessibility of spatially referenced digital data. Perhaps more importantly, we have no way of prejudging the scale at which strategically important research may be conducted, or at which its effects can best be represented. We propose that continued development of the technical means and human capacity to define problem-specific divisions of agroecological space would better serve the on-going pursuit of cost-effective investments in the agricultural sciences. There is no need to disregard some of the important variability contained in the underlying biophysical data, nor to needlessly blur the focus on the nature and severity of agroecological constraints that are most relevant for the proper targeting of R&D.

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